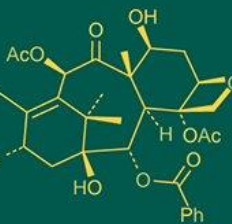
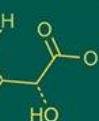
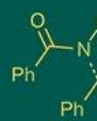


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Samta Sankhwar
M.Sc. (Ag.) Horticulture
(Vegetable Science), Faculty of
Agricultural Sciences and
Allied Industries, Rama
University, Mandhana,
Kapur, Uttar Pradesh, India

Jitendra Kumar
Assistant Professor,
Horticulture (Vegetable
Science), Faculty of
Agricultural Sciences and
Allied Industries, Rama
University, Mandhana,
Kapur, Uttar Pradesh, India

Corresponding Author:
Samta Sankhwar
M.Sc. (Ag.) Horticulture
(Vegetable Science), Faculty of
Agricultural Sciences and
Allied Industries, Rama
University, Mandhana,
Kapur, Uttar Pradesh, India

Influence of GA₃ and NAA foliar application on vegetative growth, yield attributes and quality enhancement in cabbage

Samta Sankhwar and Jitendra Kumar

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Abstract

A field experiment was conducted during the Rabi season of 2025-26 at the Agricultural Research Farm, Rama University, Mandhana, Kapur, Uttar Pradesh, India to evaluate the effect of Gibberellic Acid (GA₃) and Naphthalene Acetic Acid (NAA) on growth, yield and quality parameters of cabbage (*Brassica oleracea* var. *capitata* L.) cv. Pusa Drumhead. The experiment was laid out in a Randomized Block Design with nine treatments and three replications comprising different concentrations of GA₃ and NAA applied individually and in combination as foliar sprays. The results revealed significant variation among treatments for all growth, yield and quality parameters. Among the treatments, combined application of GA₃ @ 75 ppm + NAA @ 40 ppm (T₉) recorded the maximum plant height (35.6 cm), number of leaves (18.1), leaf area (695.7 cm²), head diameter (18.5 cm), head weight (1.68 kg plant⁻¹), marketable yield (16.8 kg plot⁻¹) and total yield (62.7 t ha⁻¹). The same treatment also produced superior quality attributes with maximum chlorophyll content (52.4 SPAD), vitamin C (42.1 mg 100 g⁻¹ FW), total soluble solids (5.9 °Brix) and shelf life (10.8 days). The study concluded that combined foliar application of GA₃ and NAA exerted a synergistic effect on physiological efficiency, assimilate partitioning and productivity of cabbage, thereby significantly improving growth, yield and quality under field conditions.

Keywords: Foliar application, Vegetative growth, Head compactness, Chlorophyll content, Marketable yield, Total soluble solids

Introduction

Cabbage (*Brassica oleracea* var. *capitata* L.) is one of the most important cole crops belonging to the family Brassicaceae with a chromosome number of 2n = 18. It is widely cultivated in temperate and subtropical regions because of its adaptability, high productivity and nutritional importance. The crop is characterized by a short stem bearing compact overlapping leaves that form the edible head. Cabbage is consumed in both raw and cooked forms and is extensively utilized in salads, soups, curries, pickles and processed food products. The characteristic flavor of cabbage is mainly attributed to the presence of sulfur-containing glucosides such as sinigrin (Wieczorek and Drabinska, 2022) [34]. In addition to its culinary importance, cabbage possesses several medicinal and health-promoting properties due to the presence of glucosinolates, flavonoids, phenolic compounds and antioxidants, which exhibit anti-inflammatory and anticancer activities (Shinali *et al.*, 2024; Uddin *et al.*, 2025) [31, 33].

Nutritionally, cabbage is considered a rich source of vitamin C, carotene, dietary fiber, minerals and antioxidants that contribute significantly to human health by enhancing immunity, improving digestion and preventing various metabolic disorders (Saba *et al.*, 2025; Daniel *et al.*, 2023) [29, 7]. The edible portion of cabbage contains high moisture along with appreciable quantities of carbohydrates, proteins, calcium, potassium and iron, making it an important component of a balanced diet (Abu *et al.*, 2024) [1]. Due to its low calorific value and high nutritive content, cabbage has gained widespread popularity among consumers worldwide.

Globally, cabbage is cultivated on approximately 2.47 million hectares with a production of about 71.26 million metric tonnes and an average productivity of 28.81 metric tonnes per hectare (FAO STAT, 2016). China ranks first in cabbage production, followed by India,

which is one of the leading producers of cabbage globally (FAO STAT, 2016). In India, cabbage is cultivated over an area of about 442 thousand hectares with a production of nearly 10.43 million metric tonnes and an average productivity of 23.6 metric tonnes per hectare (Govt. of India, MoAFW, 2025). Despite large-scale cultivation, the productivity of cabbage in India remains comparatively lower than several developed countries due to inadequate nutrient management, poor crop management practices and limited use of advanced technologies (Goswami *et al.*, 2025) [16].

Plant growth regulators (PGRs) are organic substances that influence physiological and biochemical processes in plants even at very low concentrations. These compounds regulate growth and development by affecting cell division, cell elongation, photosynthesis, nutrient uptake and assimilate translocation. In modern vegetable production, plant growth regulators are widely used for improving vegetative growth, yield and quality parameters of crops (Islam and Mohammad, 2022; Jan *et al.*, 2023) [18, 19].

Among various growth regulators, Gibberellic Acid (GA₃) and Naphthalene Acetic Acid (NAA) are considered highly effective for improving growth and productivity in vegetable crops. GA₃ is a naturally occurring diterpenoid hormone known to promote stem elongation, leaf expansion, chlorophyll synthesis and enhanced photosynthetic activity. It also stimulates enzyme activity and regulates carbohydrate metabolism, resulting in improved vegetative growth and biomass accumulation (Bagale *et al.*, 2022) [3]. NAA, a synthetic auxin, plays an important role in cell division, root development, nutrient mobilization and delayed senescence, thereby enhancing overall plant growth and productivity (Jiang *et al.*, 2025) [20].

The combined application of GA₃ and NAA has been reported to exhibit synergistic effects in cabbage and other cole crops by improving vegetative growth, head compactness, marketable yield and quality parameters (Tavallali and Darvishzadeh, 2025) [32]. The interaction between these growth regulators positively influences physiological processes such as photosynthesis, assimilate partitioning and hormonal balance within the plant system (Naher, 2021) [25]. Earlier findings also indicated that lower concentrations of NAA improved recovery of transplanted seedlings and reduced mortality (Chhonkar and Jha, 1963) [5], whereas GA₃ application promoted rapid growth, early head formation and improved quality characteristics in cabbage (Chhonkar and Singh, 1964) [6]. Furthermore, metabolomics-assisted studies have highlighted the importance of metabolite profiling in understanding plant physiological enhancement and biochemical modulation

mediated by bioactive compounds and nano-enabled agricultural interventions (Gautam *et al.*, 2025a, Gautam *et al.*, 2024) [10, 15].

Considering the increasing demand for cabbage and the need to enhance productivity and quality under field conditions, the present investigation was undertaken to evaluate the effect of different concentrations of GA₃ and NAA, applied individually and in combination, on growth, yield and quality parameters of cabbage cv. Pusa Drumhead during the Rabi season of 2025-26. The study aimed to identify the most suitable plant growth regulator treatment for improving vegetative growth, head development, yield and quality of cabbage under agro-climatic conditions of Uttar Pradesh.

Materials and Methods

Experimental Site and Geographical Location

The present investigation entitled “Effect of GA₃ and NAA on Growth, Yield and Quality of Cabbage (*Brassica oleracea* var. capitata L.)” was conducted during the Rabi season of 2025-26 at the Agricultural Research Farm, Rama University. The experimental farm is situated in the Indo-Gangetic Plain under the Central Plain Zone of Uttar Pradesh, India. Geographically, the experimental site is located between 26°34’ to 26°56’ North latitude and 80°13’ to 80°21’ East longitude at an altitude of 125.9 m above mean sea level. The region falls under subtropical climatic conditions and is characterized by hot summers and cool winters, which are suitable for successful cultivation of cabbage during the Rabi season.

Crop and Variety

The experimental crop selected for the present study was cabbage (*Brassica oleracea* var. capitata L.) cv. Pusa Drumhead, a widely cultivated mid-season variety developed by the Indian Agricultural Research Institute in 1957. The variety is known for its vigorous growth, compact heads and adaptability under North Indian agro-climatic conditions, making it suitable for cultivation during the Rabi season.

Treatment Details

The experiment comprised different concentrations of plant growth regulators, namely Gibberellic Acid (GA₃) and Naphthalene Acetic Acid (NAA), applied as foliar sprays individually and in combination to evaluate their effect on growth, yield and quality parameters of cabbage. A total of nine treatments including one control were tested under Randomized Block Design (RBD).

Table 1: Treatment combinations of plant growth regulators (GA₃ and NAA) applied as foliar sprays in cabbage to evaluate their effect on growth, yield and quality parameters

Treatments	Combinations
T ₁	Control (no PGR application)
T ₂	GA ₃ Foliar spray @ 25 ppm
T ₃	GA ₃ Foliar spray @ 50 ppm
T ₄	GA ₃ Foliar spray @ 75 ppm
T ₅	NAA Foliar spray @ 20 ppm
T ₆	NAA Foliar spray @ 40 ppm
T ₇	NAA Foliar spray @ 60 ppm
T ₈	GA ₃ Foliar spray @ 50 ppm + NAA Foliar spray @ 40 ppm
T ₉	GA ₃ Foliar spray @ 75 ppm + NAA Foliar spray @ 40 ppm

Growth Parameters

Plant height was measured from the ground level to the tip of the uppermost leaf of five randomly selected plants using a measuring tape at 30, 45 and 60 days after transplanting (DAT) and the average value was expressed in centimeters. The number of leaves per plant was recorded by counting fully developed non-wrapper leaves longer than 2.5 cm at 30, 45 and 60 DAT and the mean value was calculated.

Leaf area was measured using a digital leaf area meter. Fully expanded healthy leaves were collected from randomly selected plants of each treatment and the leaf area was recorded in square centimeters (cm²). Days to head initiation were recorded as the number of days from transplanting to the commencement of head formation.

Yield Attributes and Yield

Head diameter was measured in centimeters after harvest using thread measurement and the average value was computed. Head weight was determined by weighing five randomly selected heads from each treatment and expressed in kg plant⁻¹. Marketable yield per plot was calculated by weighing the total marketable heads harvested from each plot and expressed in kilograms per plot. Yield per hectare was computed on the basis of yield obtained per plot and expressed in tonnes per hectare.

Head compactness index was calculated following the method suggested by Pearson using the formula:

$$\text{Head Compactness Index} = \frac{\text{Head Weight (kg)}}{\text{Polar Diameter} \times \text{Equatorial Diameter}}$$

Total biomass yield was recorded by uprooting whole plants from each treatment at harvest, removing adhered soil particles and weighing the fresh biomass using a digital balance.

Quality Parameters

Chlorophyll content was measured using a SPAD chlorophyll meter from fully expanded leaves and expressed as SPAD value. Three readings per leaf were recorded and averaged. Vitamin C content was estimated by the 2,6-dichlorophenol indophenol dye titration method. Fresh cabbage samples were homogenized with 3% metaphosphoric acid, filtered and titrated against standard dye solution and the results were expressed as mg 100 g⁻¹ fresh weight. Total soluble solids (TSS) were measured using a hand refractometer from fresh cabbage juice and expressed in °Brix. Shelf life was assessed by storing healthy cabbage heads under ambient conditions and recording the number of days until deterioration in marketable quality was observed.

Result

Effect of GA₃ and NAA on Growth Parameters of Cabbage

The application of different concentrations of gibberellic acid (GA₃) and naphthalene acetic acid (NAA), either individually or in combination, significantly influenced the

vegetative growth parameters of cabbage. The observations pertaining to plant height, number of leaves per plant, leaf area and days to head initiation are presented in Table 1 and Figure 1. The results clearly indicated that combined application of GA₃ and NAA produced superior growth performance compared to their individual application and untreated control.

Plant Height

Plant height increased progressively with crop growth from 30 to 60 DAT under all treatments. Significant differences among treatments were observed at all growth stages (Table 2; Figure 1). At 30 DAT, the highest plant height was recorded in treatment T₉ (GA₃ @ 75 ppm + NAA @ 40 ppm) with 18.9 cm, which was statistically at par with T₈ (18.5 cm), while the lowest plant height was observed in the control treatment T₁ (16.4 cm). Similar trends were recorded at 45 and 60 DAT, where T₉ recorded maximum plant heights of 30.6 cm and 35.6 cm, respectively, followed by T₈ with 29.3 cm and 34.3 cm. The control treatment consistently recorded the minimum values of 22.5 cm and 28.9 cm at 45 and 60 DAT, respectively.

Number of Leaves per Plant

The number of leaves per plant was significantly affected by different treatments throughout the crop growth period (Table 2; Figure 1). At 30 DAT, treatment T₉ recorded the maximum number of leaves (12.2), followed by T₈ (11.8), whereas the minimum number of leaves was recorded under control T₁ (10.2). At 45 DAT, the highest number of leaves was again observed in T₉ (14.6), followed by T₈ (14.1), while T₁ recorded the lowest value of 11.5 leaves. Similar observations were recorded at 60 DAT, where T₉ produced the maximum number of leaves (18.1), whereas control treatment recorded only 14.2 leaves per plant.

Leaf Area

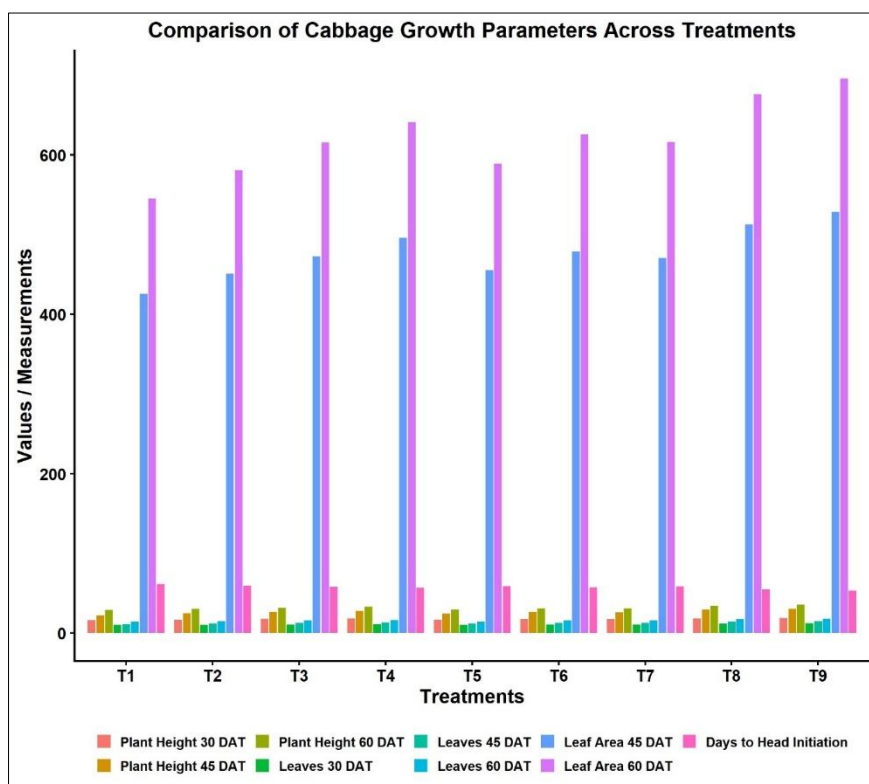
Leaf area is an important growth attribute directly associated with photosynthetic efficiency and biomass accumulation. The data indicated significant variation in leaf area among treatments at both 45 and 60 DAT (Table 2; Figure 1). The maximum leaf area was recorded under treatment T₉ with 528.4 cm² at 45 DAT and 695.7 cm² at 60 DAT. This was followed by treatment T₈, which recorded 512.6 cm² and 675.9 cm² leaf area at corresponding stages. The minimum leaf area was observed under control treatment T₁ with 425.6 cm² at 45 DAT and 545.3 cm² at 60 DAT.

Days to Head Initiation

The treatments significantly influenced the number of days required for head initiation (Table 2; Figure 1). Among all treatments, the earliest head initiation was observed under T₉ (53.5 days), followed by T₈ (54.8 days), indicating the positive influence of combined growth regulator application on crop earliness. On the contrary, the control treatment required the maximum number of days (61.4 days) for head initiation.

Table 2: Effect of GA₃ and NAA on Growth Parameters of Cabbage

Treatments	Plant Height (cm) 30 DAT	Plant Height (cm) 45 DAT	Plant Height (cm) 60 DAT	No. of Leaves 30 DAT	No. of Leaves 45 DAT	No. of Leaves 60 DAT	Leaf Area (cm ²) 45 DAT	Leaf Area (cm ²) 60 DAT	Days to Head Initiation
T ₁ - Control	16.4	22.5	28.9	10.2	11.5	14.2	425.6	545.3	61.4
T ₂ - GA ₃ @ 25 ppm	17.1	24.9	30.4	10.4	11.9	14.6	450.8	580.6	59.6
T ₃ - GA ₃ @ 50 ppm	17.8	26.6	31.8	10.8	13	15.8	472.5	615.4	58
T ₄ - GA ₃ @ 75 ppm	18.3	28.1	33.1	11.1	13.5	16.4	495.7	640.8	56.8
T ₅ - NAA @ 20 ppm	16.9	24.3	29.7	10.5	12	14.5	455.2	588.6	59.1
T ₆ - NAA @ 40 ppm	17.4	26.4	31.2	10.7	12.8	15.6	478.9	625.7	57.4
T ₇ - NAA @ 60 ppm	17.6	26.1	31	11	12.7	15.9	470.3	615.8	58.2
T ₈ - GA ₃ 50 ppm + NAA 40 ppm	18.5	29.3	34.3	11.8	14.1	17.4	512.6	675.9	54.8
T ₉ - GA ₃ 75 ppm + NAA 40 ppm	18.9	30.6	35.6	12.2	14.6	18.1	528.4	695.7	53.5
SEm (±)	0.6	0.82	1.01	0.34	0.41	0.47	15.6	18.4	1.63
CD (P=0.05)	1.8	2.46	3.03	1.02	1.23	1.41	46.8	55.2	4.89

**Fig 1:** Growth parameters of cabbage as influenced by GA₃ and NAA treatments.

Effect of GA₃ and NAA on Yield Attributes and Yield of Cabbage

The data pertaining to yield attributes and yield of cabbage as influenced by different concentrations of GA₃ and NAA are presented in Table 4 and Figure 2. The results revealed that the application of plant growth regulators significantly improved head diameter, head weight, head compactness index, marketable yield per plot, total yield per hectare and total biomass yield over the control treatment. Among all the treatments, the combined application of GA₃ and NAA exhibited superior performance compared to their individual applications.

Head Diameter

Head diameter was significantly influenced by different treatments (Table 4; Figure 2). The maximum head diameter was recorded under treatment T₉ (GA₃ @ 75 ppm + NAA @ 40 ppm), which produced a head diameter of 18.5 cm. This treatment was followed by T₈ (GA₃ @ 50 ppm + NAA @ 40 ppm) with 17.8 cm and T₄ (GA₃ @ 75 ppm) with 17.1 cm. The minimum head diameter (14.6 cm) was observed under the control treatment (T₁).

Head Weight

A significant increase in head weight was observed with the

application of plant growth regulators (Table 4; Figure 2). The highest head weight was recorded in treatment T₉ with 1.68 kg per plant, followed by T₈ (1.58 kg per plant) and T₄ (1.46 kg per plant). The lowest head weight was recorded in the control treatment (1.12 kg per plant).

Head Compactness Index

The head compactness index was significantly affected by the treatments (Table 4; Figure 2). Treatment T₉ recorded the maximum compactness index (0.95), followed by T₈ (0.92), whereas the minimum value was recorded under control treatment T₁ (0.78). Treatments receiving combined application of GA₃ and NAA consistently produced more compact heads compared to individual applications.

Marketable Yield per Plot

Marketable yield per plot was significantly enhanced by the application of GA₃ and NAA (Table 4; Figure 2). The highest marketable yield per plot was obtained in treatment T₉ (16.8 kg), followed by T₈ (15.9 kg) and T₄ (14.7 kg). The control treatment recorded the lowest marketable yield (11.3 kg per plot).

Yield per Hectare

Significant differences among treatments were observed with respect to yield per hectare (Table 4; Figure 2). The maximum yield was recorded under treatment T₉ with 62.7 t ha⁻¹, followed by T₈ with 59.4 t ha⁻¹. The control treatment recorded the minimum yield of 42.1 t ha⁻¹. Individual application of GA₃ at 75 ppm (T₄) also produced a comparatively higher yield of 54.9 t ha⁻¹.

Total Biomass Yield

Total biomass yield was significantly affected by different treatments (Table 4; Figure 2). The highest biomass yield was recorded under T₉ (78.6 t ha⁻¹), followed by T₈ (74.8 t ha⁻¹), while the lowest biomass yield was observed under the control treatment (54.8 t ha⁻¹). The increased biomass production under combined treatments could be attributed to vigorous vegetative growth, increased leaf area, higher chlorophyll content and improved physiological activity induced by GA₃ and NAA application. Enhanced dry matter accumulation and efficient partitioning of assimilates ultimately resulted in greater total biomass production.

Table 3: Effect of GA₃ and NAA on Yield Attributes and Yield of Cabbage

Treatments	Head Diameter (cm)	Head Weight (kg/plant)	Head Compactness Index	Marketable Yield/Plot (kg)	Yield (t/ha)	Total Biomass Yield (t/ha)
T ₁ - Control	14.6	1.12	0.78	11.3	42.1	54.8
T ₂ - GA ₃ @ 25 ppm	15.4	1.21	0.81	12.1	45.3	58.7
T ₃ - GA ₃ @ 50 ppm	16.3	1.35	0.86	13.6	50.8	64.9
T ₄ - GA ₃ @ 75 ppm	17.1	1.46	0.89	14.7	54.9	69.7
T ₅ - NAA @ 20 ppm	15.1	1.18	0.8	11.8	44.1	57.2
T ₆ - NAA @ 40 ppm	16.2	1.33	0.85	13.3	49.6	63.6
T ₇ - NAA @ 60 ppm	15.9	1.3	0.84	12.9	48.2	61.8
T ₈ - GA ₃ 50 ppm + NAA 40 ppm	17.8	1.58	0.92	15.9	59.4	74.8
T ₉ - GA ₃ 75 ppm + NAA 40 ppm	18.5	1.68	0.95	16.8	62.7	78.6
SEm (±)	0.56	0.07	0.03	0.72	2.13	2.68
CD (P=0.05)	1.68	0.21	0.09	2.16	6.39	8.04

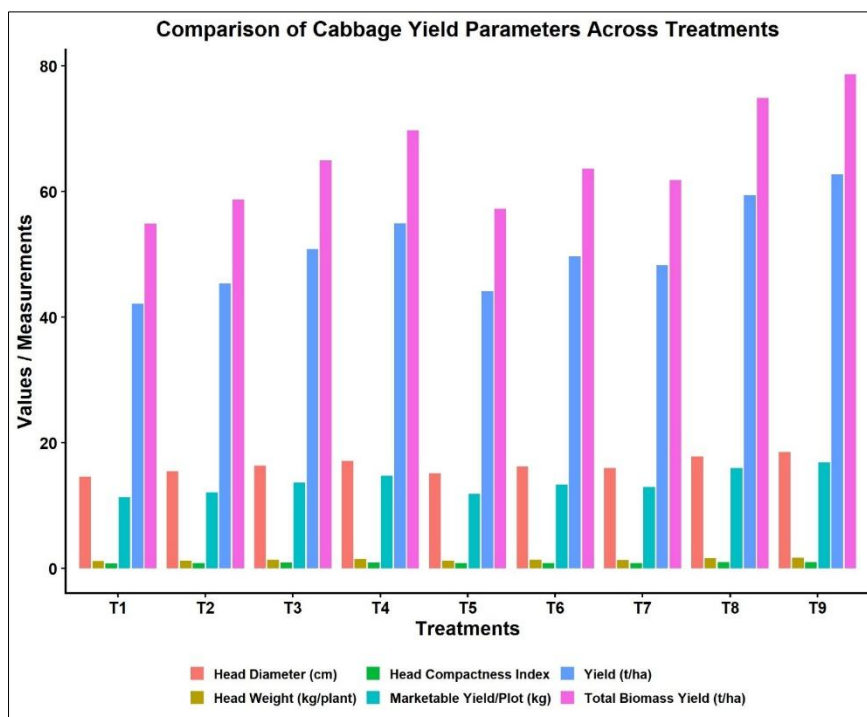


Fig 2: Yield parameters of cabbage as influenced by GA₃ and NAA treatments

Effect of GA₃ and NAA on Quality Parameters of Cabbage

The quality parameters of cabbage, namely chlorophyll content, vitamin C content, total soluble solids (TSS) and shelf life, were significantly influenced by the application of different concentrations of GA₃ and NAA either alone or in combination. The data presented in Table 4 and Figure 3 clearly indicated that combined application of GA₃ and NAA markedly improved the quality characteristics of cabbage compared to individual applications and untreated control.

Chlorophyll Content (SPAD Value)

The chlorophyll content of cabbage leaves increased significantly with the application of plant growth regulators (Table 4; Figure 3). Among the treatments, the highest chlorophyll content was recorded under treatment T₉ (GA₃ @ 75 ppm + NAA @ 40 ppm) with a SPAD value of 52.4, which was closely followed by T₈ (50.6). The lowest chlorophyll content was observed under the control treatment T₁ (41.8 SPAD units).

Vitamin C Content

Vitamin C content was significantly affected by different treatments (Table 4; Figure 3). The maximum vitamin C

content was recorded in treatment T₉ with 42.1 mg per 100 g fresh weight, followed by T₈ with 40.5 mg per 100 g fresh weight. The minimum vitamin C content (32.4 mg per 100 g fresh weight) was recorded under the control treatment.

Total Soluble Solids (TSS)

Total soluble solids content showed significant improvement with plant growth regulator application (Table 4; Figure 3). Treatment T₉ recorded the highest TSS value of 5.9 °Brix, followed by T₈ (5.6 °Brix) and T₄ (5.3 °Brix), whereas the lowest TSS value (4.6 °Brix) was observed in the control treatment.

Shelf Life

Shelf life of cabbage heads was significantly influenced by different treatments (Table 4; Figure 3). The maximum shelf life was recorded under treatment T₉ (10.8 days), followed by T₈ (10.1 days), whereas the minimum shelf life was observed under the control treatment (7.2 days). Individual application of GA₃ @ 75 ppm (T₄) also resulted in comparatively higher shelf life (9.1 days). The improvement in shelf life under combined application of GA₃ and NAA may be due to delayed senescence, maintenance of tissue firmness, reduced moisture loss and enhanced physiological stability of the heads during storage.

Table 4: Effect of GA₃ and NAA on Quality Parameters of Cabbage

Treatments	Chlorophyll Content (SPAD)	Vitamin C (mg/100 g FW)	Total Soluble Solids (°Brix)	Shelf Life (days)
T ₁ - Control	41.8	32.4	4.6	7.2
T ₂ - GA ₃ @ 25 ppm	43.9	34.1	4.8	7.8
T ₃ - GA ₃ @ 50 ppm	46.2	36.8	5.1	8.6
T ₄ - GA ₃ @ 75 ppm	48.5	38.7	5.3	9.1
T ₅ - NAA @ 20 ppm	44.6	34.9	4.9	8
T ₆ - NAA @ 40 ppm	46	36.5	5.1	8.7
T ₇ - NAA @ 60 ppm	45.7	35.9	5	8.4
T ₈ - GA ₃ 50 ppm + NAA 40 ppm	50.6	40.5	5.6	10.1
T ₉ - GA ₃ 75 ppm + NAA 40 ppm	52.4	42.1	5.9	10.8
SEm (±)	1.69	1.28	0.19	0.42
CD (P=0.05)	5.07	3.84	0.57	1.26

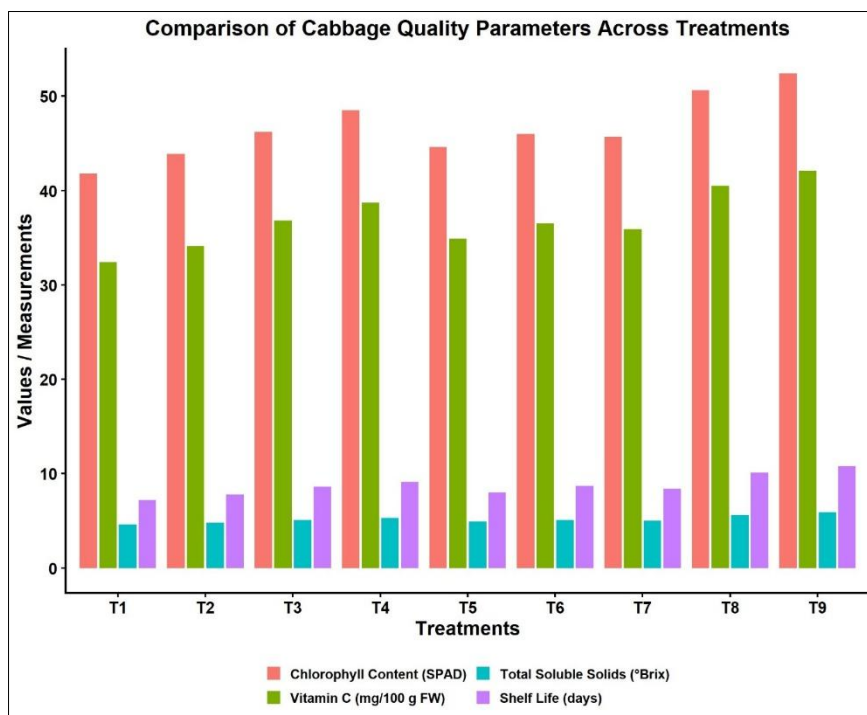


Fig 3: Quality parameters of cabbage as influenced by GA₃ and NAA treatments.

Discussion

The present investigation demonstrated that foliar application of GA₃ and NAA significantly influenced the growth, yield and quality parameters of cabbage. Among all treatments, the combined application of GA₃ @ 75 ppm + NAA @ 40 ppm (T₉) proved most effective in improving vegetative growth, head development, yield and quality characteristics of cabbage. The superior performance of combined treatments over individual applications indicated a synergistic interaction between gibberellic acid and naphthalene acetic acid.

The significant increase in plant height, number of leaves and leaf area observed under combined GA₃ and NAA treatments may be attributed to enhanced cell division, cell elongation and improved assimilate translocation within the plant system. Gibberellic acid is known to stimulate internodal elongation and chlorophyll biosynthesis, while NAA enhances nutrient uptake and metabolic activity, resulting in vigorous vegetative growth. Increased leaf area under these treatments might have improved light interception and photosynthetic efficiency, thereby enhancing biomass accumulation and early head initiation. Similar findings were reported by Rajpoot *et al.* (2025) [27], Patel *et al.* (2024) [26], Kumar *et al.* (2023) and Moniruzzaman *et al.* (2019) [24], who observed significant improvement in vegetative growth of cabbage following GA₃ and NAA application. Recent metabolomics-based investigations have further highlighted the importance of physiological and biochemical modulation in enhancing plant performance under different biotic interactions and management practices (Gautam *et al.*, 2025b) [11].

The reduction in days to head initiation under combined treatments may be associated with accelerated vegetative growth and rapid accumulation of photosynthates, which promoted earlier transition from vegetative to reproductive phase. Similar observations were reported by Saravaiya *et al.* (2010) [30] and Meena *et al.* (2018) [23] in cabbage and cauliflower, respectively.

Yield attributes and yield were also significantly enhanced by plant growth regulator treatments. The highest head diameter, head weight, compactness index, marketable yield and total biomass yield recorded under T₉ may be attributed to increased photosynthetic activity, efficient assimilate partitioning and enhanced sink strength of developing heads. The improved vegetative growth under GA₃ and NAA treatments likely resulted in greater synthesis and translocation of carbohydrates toward the cabbage head, thereby increasing head size and weight. Gibberellins promote cell expansion and growth, whereas auxins improve nutrient mobilization and structural development of plant tissues, leading to compact and heavier heads. Similar findings were reported by Rajpoot *et al.* (2025) [27], Ahmed *et al.* (2019) [2], Moniruzzaman *et al.* (2019) [24], Dev *et al.* (2020) [8] and Dhengle and Bhosale (2008) [9], who observed increased cabbage yield with GA₃ and NAA application. Comparable improvements in crop performance associated with physiological regulation and host response mechanisms have also been documented in recent studies on plant-pathogen interactions and resistance evaluation (Gautam *et al.*, 2025c) [12].

The improvement in chlorophyll content, vitamin C, total soluble solids and shelf life under combined treatments indicated enhanced physiological efficiency and better biochemical composition of cabbage heads. Increased

chlorophyll content under GA₃ treatments may be due to enhanced chloroplast development and delayed chlorophyll degradation, resulting in higher photosynthetic efficiency. Improved vitamin C and TSS content might be associated with increased carbohydrate metabolism and accumulation of soluble sugars under the influence of plant growth regulators. The enhanced shelf life observed under combined treatments could be attributed to delayed senescence, improved tissue firmness and reduced physiological deterioration during storage. Similar results were reported by Rajpoot *et al.* (2025) [27], Chauhan and Tandel (2009) [4], Roy and Nasiruddin (2011) [28] and Kottapu *et al.* (2023) [21]. Furthermore, recent studies have emphasized the importance of alternative host interactions and physiological adaptability in regulating plant performance and productivity under varying environmental conditions (Gautam *et al.*, 2026) [14].

Overall, the findings of the present study clearly indicated that the combined application of GA₃ @ 75 ppm + NAA @ 40 ppm was highly effective in enhancing growth, yield and quality parameters of cabbage under field conditions. The synergistic interaction between GA₃ and NAA improved physiological and metabolic activities, ultimately resulting in superior crop performance and productivity.

Conclusion

The present investigation clearly demonstrated that the application of plant growth regulators significantly influenced the growth, yield and quality parameters of cabbage under field conditions. Among the various treatments evaluated, the combined foliar application of GA₃ @ 75 ppm + NAA @ 40 ppm (T₉) proved to be the most effective treatment for improving vegetative growth, head development, yield and quality attributes of cabbage. The treatment significantly enhanced plant height, number of leaves, leaf area and promoted earlier head initiation compared to the control. Similarly, yield attributes such as head diameter, head weight, head compactness index, marketable yield, total yield and biomass yield were markedly increased under combined application of GA₃ and NAA. Quality parameters including chlorophyll content, vitamin C, total soluble solids and shelf life were also significantly improved, indicating enhanced physiological efficiency and better biochemical composition of cabbage heads. The synergistic interaction between GA₃ and NAA likely improved photosynthetic activity, nutrient translocation and assimilate partitioning, resulting in superior crop performance.

Future research should focus on evaluating different combinations and application timings of plant growth regulators under varying agro-climatic conditions and across diverse cabbage cultivars. Integration of GA₃ and NAA with nutrient management and sustainable cultivation practices may further help in developing economically feasible and environmentally sustainable cabbage production technologies.

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